Search for Higgs bosons decaying to aa in the $\mu\mu\tau\tau$ final state in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS experiment

Phys. Rev. D 92, 05002

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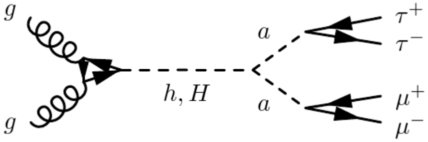
Physics Motivation



Exotic Decay of SM-like Higgs, *h*

Coupling measurements allow for non-SM decays up to BR $\sim$ O(40%), at 95% CL

Consider a new pseudo-scalar Higgs boson, *a*

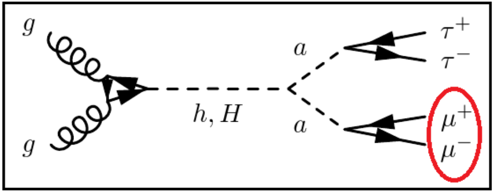
- Focus on, i.e. optimize selection for, $2 \cdot m_\tau < m_a < 2 \cdot m_b$
  - Leptons from *a* decay will be highly collimated
  - We extend analysis above $2 \cdot m_b$ in case couplings to quarks are suppressed
- Coupling related to mass of decay products $\Rightarrow$ *large BR($a \rightarrow \tau\tau$) at low mass*
- $a \rightarrow \mu\mu$ gives a narrow resonance $\Rightarrow$ *clean experimental signature*
- One previous search for this signature from D∅, which had no sensitivity

The Next-to-Minimal-Supersymmetric Standard Model

- The NMSSM is a well-motivated (and quite popular) SUSY model

  D. Curtin *et. al.*, Phys. Rev. D **90**, no. 7, 075004 (2014)
- Naturally achieves $m_h = 125$ GeV
- Notable in that it predicts an additional light pseudoscalar Higgs bosons (*a*)
- Also predicts another scalar Higgs, *H*, which can decay $H \rightarrow aa$

Analysis Overview

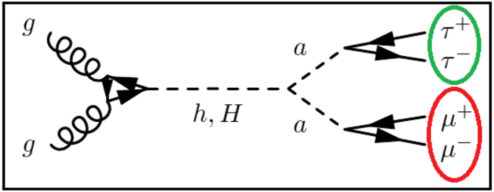


1. Pre-select $\mu^{\pm}\mu^{\mp}$ events

Strategy: Use $a \rightarrow \mu\mu$ resonance to perform a bump-hunt

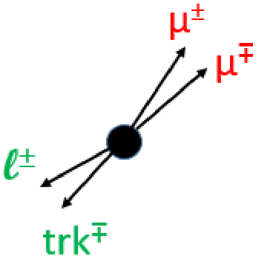
- We use single and dimuon triggers
- Require 2 isolated* muons, with p_T >16 GeV
  *For lower a masses, the muons will be collimated. We correct the isolation variable to account for this
- They must be OS and $p_T(\mu\mu)$ >40 GeV

Analysis Overview



1. Pre-select $\mu^\pm\mu^\mp$ events
2. Signal Selection: $\mu^\pm\mu^\mp+\ell^\pm\text{trk}^\mp$

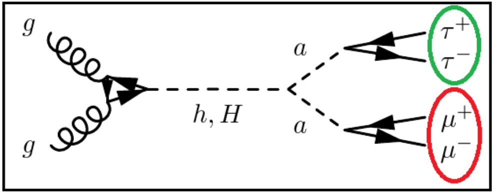
Detector Signature:



Optimize SR for selecting $a \to \tau\tau$

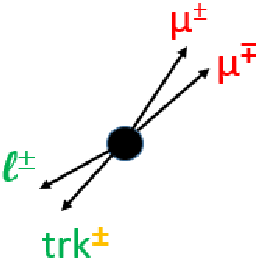
- Best sensitivity found for at least one $\tau \to \ell$
- Other τ decay inclusive
  $\Rightarrow$ Require 1, 2, or 3 nearby tracks
- Lead track carries charge of τ
  $\Rightarrow$ ℓ and leading track are OS
- Two SRs based on ℓ flavor

Analysis Overview



1. Pre-select $\mu^\pm\mu^\mp$ events
2. Signal Selection: $\mu^\pm\mu^\mp + \ell^\pm$trk$^\mp$
3. Validation: $\mu^\pm\mu^\mp + \ell^\pm$trk$^\pm$

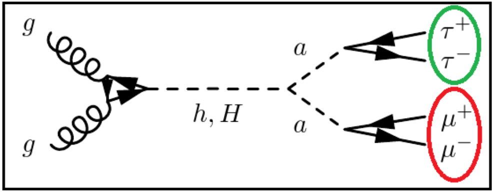
Detector Signature:



Test methods in validation regions

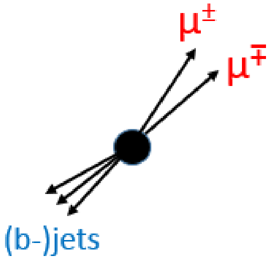
- Invert OS requirement on ℓ and leading track
- Comparable backgrounds, but no signal
- Two VRs based on ℓ flavor

Analysis Overview



1. Pre-select $\mu^{\pm}\mu^{\mp}$ events
2. Signal Selection: $\mu^{\pm}\mu^{\mp}+\ell^{\pm}trk^{\mp}$
3. Validation: $\mu^{\pm}\mu^{\mp}+\ell^{\pm}trk^{\pm}$
4. Control: $\mu^{\pm}\mu^{\mp}$+(b-)jets

Detector Signature:



Measure backgrounds in control regions

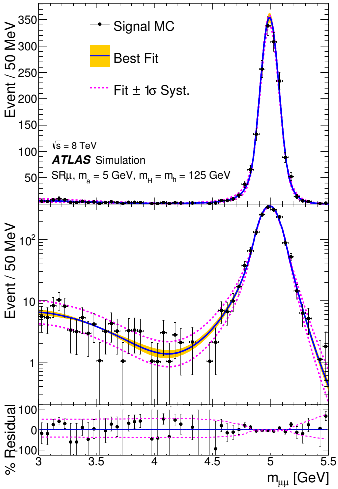
- Replace $\tau\tau$ selection with jets
- Two CRs for light- and heavy- flavor backgrounds

Fitting Strategy

Perform a bump hunt in $m_{\mu\mu}$ from 3.7 to 50 GeV in SRs

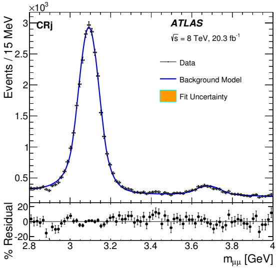
- Background and signal models measured in the data!
- Use simulation to study shapes
- Need a robust background model for entire mass range
  1. Non-resonant background (mainly DY)
  2. $t\bar{t}$ background
  3. SM (J/ψ, Υ, Z)
     - The J/ψ is used to constrain the ψ'
     - The low-end Z tail can be significant above 40 GeV
     - All resonances assumed to have a *narrow width*
- Use a common shape for all narrow $\mu\mu$ resonances

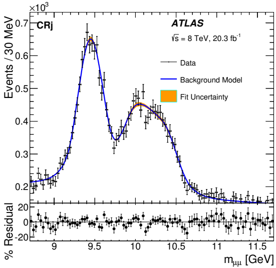
The Narrow $\mu\mu$ Resonances



$X \to \mu\mu$ Double-Sided Crystal Ball

- Gaussian core, low- and high-end power laws
- 3 free parameters, μ_{CB}, σ_{CB}, α_{CB} *measured in data*
- Mean (μ_{CB}), width (σ_{CB}) linearly depend on m_X
- Tested on 24 signal samples*, varying m_a and m_H
- Fit to SM resonances *in data* shown below

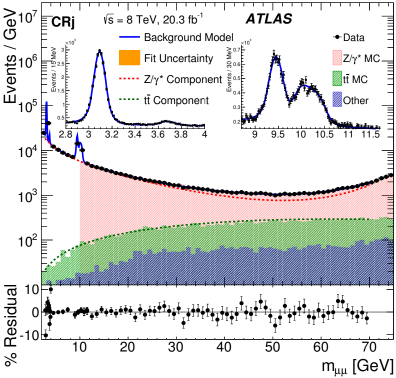




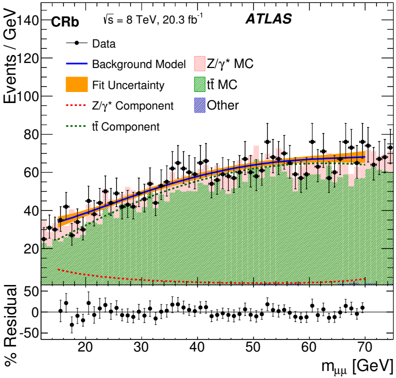
* Details on signal shape (low mass tail and systematics) can be found in the backup

Background Measurement

CRj: $\tau\tau(\ell + trk) \Rightarrow \geq 1$ jet



CRb: $\tau\tau(\ell + trk) \Rightarrow \geq 2$ b-jets

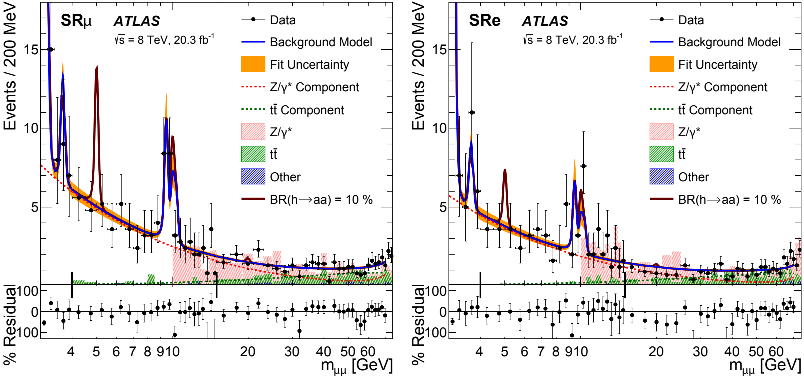


- Results used to constrain fit to SRs

Some details...

- Resonant backgrounds (J/Ψ, Υ, Z) use a double-sided Crystal Ball
  - Three CB parameters shared with $a \to \mu\mu$ resonance
- Drell–Yan background modeled by $P_{\gamma^*} = e^{\alpha_{\gamma^*} \cdot m_{\mu\mu}} (m_{\mu\mu})^{n_{\gamma^*}}$
- $t\bar{t}$ modeled by Rayleigh distribution: $P_{tt} = m_{\mu\mu} \times Gaus(m_{\mu\mu}|\mu_{tt} = 0, \sigma_{tt})$

Results: Fit to Signal Region



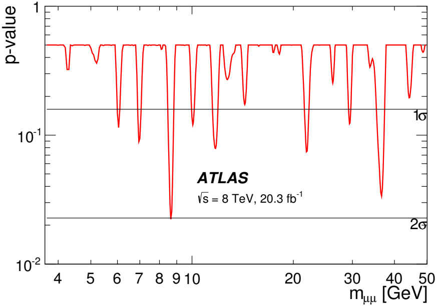
Constrained from Fit to CR

- Background shape parameters (2 for γ^*, 1 for $t\bar{t}$, multiple for SM resonances)
- Relative contributions of higher Ψ and Υ spin states
- Relative contribution of Z to total Z/γ^*

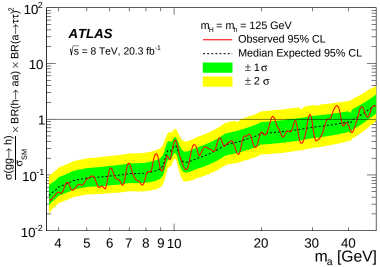
Unconstrained:Relative contributions of Ψ, Υ, $t\bar{t}$ and Z/γ^*

Simulated signal shown in brown for $m_a = 5$, 10 and 20 GeV

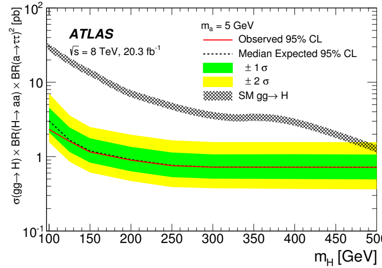
Results: Statistical Analysis



Scan vs. m_a for 125 GeV Higgs:



Scan vs. m_H (new heavy scalar) for 5 GeV a boson:



- Observation consistent with SM
- Min p-value = 0.022 for $m_{\mu\mu} = 8.65$ GeV
- Global p-value > 0.5
- Upper limit on $BR(h \to aa)$ as low as 3.5% for $m_a = 3.75$ GeV, $m_h = 125$ GeV
- Upper limit on $BR(H \to aa) \times \sigma(gg \to H)$ from 2.33 to 0.72 pb, for $m_a = 5$ GeV
- Compare to D∅ result: BR($h \to aa$) > 100%

Concluding Thoughts

- These are the first limits on this *well motivated* channel from the LHC

- They are the first ever to have sensitivity to BSM physics

- The NMSSM is getting a lot of attention during Run 2, in this channel and others, so...
  STAY TUNED!

Backup

'a' Mass

$m_a < 2m_\tau$: $a \rightarrow \mu\mu(ee)$

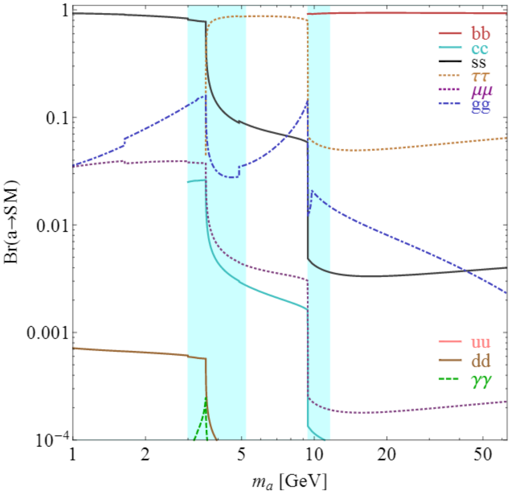
- Covered by ATLAS lepton-jets analysis

$2m_\tau < m_a < 2m_b$: $a \rightarrow \tau\tau$

- 4τ final states are hard!
- We require 1 $a \rightarrow \mu\mu$ and take a 1% hit in BR
- **Prime focus of this analysis**

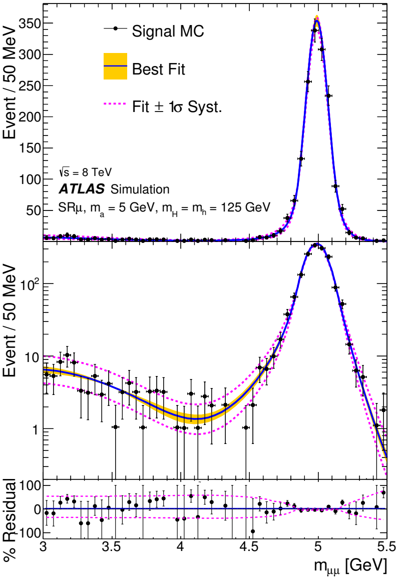
$2m_b < m_a$: $a \rightarrow bb$

- 4b final states are hard!
- $2\mu2\tau$ down by O(0.01) Interesting in case decay to b's (quarks) are suppressed.



D. Curtin et al., arXiv:1312.4992 [hep-ph]

Signal Model



$a \to \mu\mu$ Double-Sided Crystal Ball

- Gaussian core, low- and high-end power laws
- 3 free parameters, μ_{CB}, σ_{CB}, α_{CB} *measured in data*
- Width (σ_{CB}) enhanced for large m_H *determined in simulation*

$a \to \tau\tau \to \mu\mu$ Gaussian Tail

- Mean and width set proportional to CB *determined in simulation*
- Width was no m_H dependence
- Fraction of $\tau\tau$, $f_{\tau\tau}$ *determined in simulation*

Systematics*

Shape: Parameters measured in data.
Extra uncert. on α_{CB} and $f_{\tau\tau}$ to cover tails

Norm.: dom. by theory (11%)

*details in backup

Systematics

Background Model: Use spurious signal method:
Perform S+B fit to high stat. bkg-only sample

Signal Model: Parameters measured in data.
Extra systematics on α_{CB} and $f_{\tau\tau}$ parameters, to ensure coverage of tails

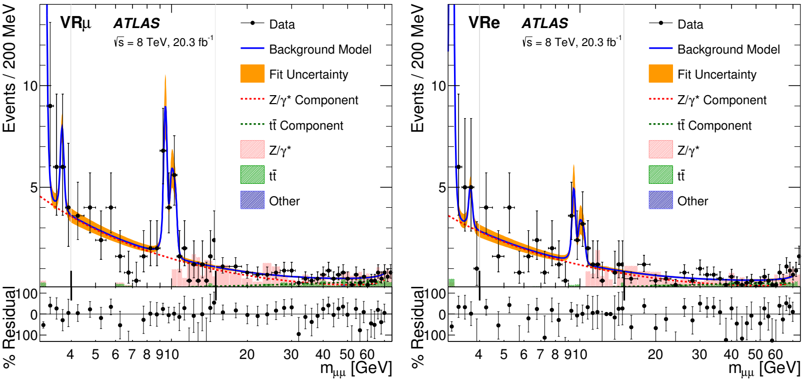
Signal Normalization: Dominant sources:

1. Theory systematic (only applicable to limit vs. m_a): 11%
2. Track momentum: vary track p_T by 2% $\Rightarrow$ 5% change in signal acceptance

Sub-Dominant Sources: trigger efficiency, the lepton reconstruction efficiency, the lepton energy scale and resolution, and the charge of the track

Fits in the Validation Region

Based on SR's, but require 3^{rd} lepton and track to be **SS**



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